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METHODS OF MEASUREMENT

Methods of Measurement in epidemiology: Sedentary Behaviour

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Background Research examining sedentary behaviour as a potentially independent risk factor for chronic disease morbidity and mortality has expanded rapidly in recent years.

Methods We present a narrative overview of the sedentary behaviour measurement literature. Subjective and objective methods of measuring sedentary behaviour suitable for use in population-based research with children and adults are examined. The validity and reliability of each method is considered, gaps in the literature specific to each method identified and potential future directions discussed.

Results To date, subjective approaches to sedentary behaviour measurement, e.g. questionnaires, have focused predominantly on TV viewing or other screen-based behaviours. Typically, such measures demonstrate moderate reliability but slight to moderate validity. Accelerometry is increasingly being used for sedentary behaviour assessments; this approach overcomes some of the limitations of subjective methods, but detection of specific postures and postural changes by this method is somewhat limited. Instruments developed specifically for the assessment of body posture have demonstrated good reliability and validity in the limited research conducted to date. Miniaturization of monitoring devices, interoperability between measurement and communication technologies and advanced analytical approaches are potential avenues for future developments in this field.

Conclusions High-quality measurement is essential in all elements of sedentary behaviour epidemiology, from determining associations with health outcomes to the development and evaluation of behaviour change interventions. Sedentary behaviour measurement remains relatively under-developed, although new instruments, both objective and subjective, show considerable promise and warrant further testing.

Keywords Sedentary behaviour, epidemiology, validity, reliability

Introduction

Sedentary behaviour, typically defined as activities requiring low levels of energy expenditure (EE) that occur while sitting or lying down, has been the subject of increasing epidemiological research in recent years.[1,2] Emerging evidence indicates that various markers of sedentary behaviour, including TV viewing and total sitting time, are deleteriously associated with chronic disease morbidity and mortality, often independent of physical activity.[3–7] If causality is established, the population-attributable risk associated with the negative consequences of sedentary behaviour is potentially large because these behaviours are highly prevalent.[8] A number of countries have produced public health guidelines that include recommendations on limiting participation in sedentary behaviour.[9,10] It is, therefore, timely and necessary to outline the key measurement approaches used for the assessment of sedentary behaviour in the context of population health research.

Within a behavioural epidemiological framework,[2,11,12] development of accurate methods of measuring sedentary behaviour is the second of five stages of research, which collectively describe the spectrum of descriptive, analytic, intervention and translational research related to the study of sedentary behaviour and population health. High-quality exposure assessment is essential to identify causal associations with health outcomes, to quantify precisely the magnitude of the association and to describe dose–response relationships.[13–16] Moreover, accurate measurement is required to document patterns of, and changes in, sedentary behaviour between and within individuals over time.

The aim of this article is to provide an overview of the various methods of measuring sedentary behaviour appropriate for use in population-based studies in children and adults.[17] Issues that are considered include the validity and reliability of each measurement approach, relative strengths and limitations, processing and interpretation of the obtained data and gaps in the literature. In addition, we discuss new and emergent approaches to sedentary behaviour measurement. We followed guidelines proposed by Landis and Koch[18] in assessing the strength of evidence for reliability and validity. The various forms of validity referred to in this article are defined and discussed in detail elsewhere.[19] This article adds to the existing literature on this topic by exploring a wide range of measurement methods (subjective and objective), with consideration of their use in both children and adults. It is not our intention to provide an exhaustive review of the literature but rather to highlight key conceptual and empirical issues pertaining to each measurement method in the context of contemporary evidence. The methods of assessing sedentary behaviour can be summarized as follows:

- Subjective measures—self- and proxy-report questionnaires, diaries.
- Objective measures—accelerometers, posture monitors, heart rate (HR) monitoring and combined sensing, multi-unit monitors.

Key characteristics of the subjective and objective methods of measurement discussed in this article are summarized in Table 1.

Subjective methods

This section refers to instruments that attempt to measure the domains of sedentary behaviour (mode, context, duration and breaks) through self-report. Questionnaires are the most commonly reported method of capturing sedentary behaviour, the majority of which are self-administered, although in-person and telephone interview formats have also been used.[2,20] Other self-report methods, such as diaries, although used less frequently in epidemiological studies to date, are also considered.

Self-report questionnaires

To date, the majority of studies using self-report measures have centred on capturing daily TV-viewing time as a proxy marker of overall sedentary behaviour.[2,20,21] Many of the questionnaires used to capture TV-viewing time have not reported reliability and validity data. In those that provided psychometric data in adults, reliability coefficients were generally fair to high (test–retest $r = 0.32$–0.93), but concurrent validity was highly variable ($r = -0.19$–0.80).[20] One study that examined absolute validity reported that TV-viewing time was significantly less when measured by self-report compared with an objective measure.[22] Two recent reviews of the literature indicate that the reliability and validity of children's self-reported TV viewing are highly variable[21,23] (test–retest $r = 0.13$–0.98, majority $r < 0.50$; validity $r = -0.19$ to 0.88, majority $r < 0.50$[21]). In addition, the measurement of TV-viewing time as an indicator of total sedentary time is problematic, as this behaviour does not appear to be representative of overall sedentary behaviour.[24,25] Studies drawing inferences about the impact of overall sedentary behaviour from assessments of TV viewing should be interpreted with caution.

Other self-report questionnaires have focused more on global measures of sedentary behaviour, such as total daily sitting time, but, similarly, the measurement properties of many such instruments have not been adequately demonstrated.[26] The International Physical Activity Questionnaire (IPAQ) was designed to provide an internationally standardized method of measuring physical activity and sitting behaviour in surveillance studies.[27] The sedentary item in the IPAQ has generally been shown to have moderate reliability (Spearman $\rho > 0.7$ for test–retest data) but moderate to poor convergent validity (Spearman

Table 1 Overview of sedentary behaviour measurement methods in the context of population health research

Characteristics	Subjective			Objective			
	Self-report questionnaire	**Proxy-report questionnaire**	**Diaries**	**Accelerometry**	**Posture monitors**	**HR/Combined sensing**	**Multi-unit monitors**
Cost	Low	Low	Low	Moderate	Moderate	High	High
Population	Adults	Children/older adults	Adults	All population groups	All population groups	All population groups	Untested in children
Participant burden	Low	Low	Moderate	Low	Low/moderate	Low/moderate	Potentially high
Researcher burden	Low	Low	Moderate	Moderate	Moderate	Moderate/high	Moderate/high
Dimensions assessed	Specific behaviours, environmental and social context	Specific behaviours, environmental and social context	Specific behaviours, environmental and social context	Total sedentary time, including bouts and breaks	Time spent sitting/standing, posture transitions	Activity intensity, frequency and duration	Posture and posture transitions, activity mode
Application	Widely used, feasibility established	Widely used, feasibility established	Infrequently used, feasibility established	Widely used, feasibility established	Increasingly used, feasibility indicated	Infrequently used, feasibility indicated	Little used, feasibility unknown
Strength(s)	Information on behaviour type and context useful for intervention design	Provides data on populations not able to complete self-reports	May be used to assess concurrent behaviours	Substantial literature on application and analysis	Able to distinguish sitting/standing	Combined movement and physiological data aid identification of monitor wear time	Able to identify behaviour mode/type
Limitation(s)	Subject to recall and reporting bias	Subject to recall and reporting bias, validation studies lacking	Subject to recall and reporting bias, validation studies lacking	No consensus regarding data processing	Validation studies in free-living conditions lacking	Formal validation studies lacking	Untested in large-scale research settings

$\rho < 0.5$) when compared with objectively measured sedentary behaviour by accelerometry.[27]

Recent work has attempted to develop more refined measurement tools that assess multiple sedentary behaviours (e.g. TV viewing, reading, socializing) and/or domain-specific behaviours (e.g. sitting at work or at home and motorized travel).[26,28,29] These show promise, but further development and validation work is required. One recent study reported that when compared with accelerometer-assessed sedentary behaviour, a single-item question significantly underestimated sitting time, whereas a domain-specific questionnaire, with multiple items, more accurately assessed average sitting time.[30] However, the single-item questionnaire had preferential limits of agreement, demonstrating smaller measurement error (both random and systematic), possibly because of fewer responses being required. This may suggest that more detailed questionnaires will be needed for sedentary behaviour prevalence and surveillance studies, whereas single-item questionnaires may be more appropriate for health-related epidemiological research, where ease of use and the ability to rank behaviours of interest are the dominant requirements.

The qualitative attributes (e.g. recall period and question/response format) and mode of administration (e.g. interviewer-/self-administered) of existing self-report instruments are extremely varied. Comparison of test–retest results in adults does not clearly demonstrate that one recall period or administration format is superior to another. There is some evidence that concurrent validity may be better in adults when participants recall a typical day compared with a 7-day or 12-month recall period. However, these observations derive from studies in different populations and use different referent measures.[20] In addition, adults and children appear better able to recall sedentary behaviour for weekdays than weekends, perhaps because of greater variability in behaviour patterns at weekends.[23,26,30]

The strengths of self-report questionnaires include that they are cost-effective, readily accessible to the majority of the population and have a relatively low participant burden. Self-report tools can also be used to identify the type of behaviour and the context in which it occurs, information that may be used to inform intervention design.

A key limitation of self-report measures is that they consistently demonstrate poor validity. A major impediment to establishing validity is the lack of an accepted 'gold standard' referent measure of sedentary behaviour.[31] The use of one form of self-report to validate another is inappropriate because of the problem of correlated error. Objective methods that assess changes in posture, which thus yield a measure of sitting, offer promise in future validation studies.[32,33] A further limitation of self-report tools is that they are vulnerable to influence by cultural norms and perceived social desirability. Achieving linguistic and conceptual equivalence in the translation of self-report tools is also challenging, limiting the comparability of data collected in different populations. Unique to the field of sedentary behaviour research, assessment of the type of behaviour being undertaken is complicated by the phenomenon of concurrent behaviours (i.e. an individual may be engaged in TV viewing and mobile phone use at the same time). Therefore, data collection using global measures of self-reported sedentary behaviour rather than specific behaviour types may have greater utility in epidemiological research.

Proxy-report questionnaires

Self-report may not be appropriate for use in children, as their limited cognitive capacity may hinder accurate recall. In such circumstances, parent-proxy reports may be used to gather information on children's sedentary behaviour.[34] Informed by evidence from observational research, age limits of 10 and 14 years, below which the use of self-report measures of sedentary behaviour is believed to be inappropriate, have been proposed,[2,35] although there is likely to be considerable between-child variability. In a recent review, reliability coefficients (intra-class correlation or Pearson's r) for parental reports of children's sedentary behaviour ranged from 0.60 to 0.80.[23] Criterion and concurrent validity coefficients (Spearman or Pearson's r) were highly variable, ranging from 0.08 to 0.84.[23] At present, few studies have examined the psychometric properties of children's proxy-reported sedentary behaviour. Further work is also required to establish reporting protocols when using these methods.[2]

Diaries

Sedentary behaviour is multi-faceted and, as such, sometimes requires more detailed assessment than can be obtained by markers of overall sitting time. Moreover, certain types of behaviour, particularly those that are sporadic or intermittent in nature, may be difficult to recall accurately for a time frame of greater than a few hours. To overcome some of the problems associated with behavioural recall, diaries and ecological momentary assessment (EMA) methods have been developed.[36]

Diaries are usually time-dependent records of behaviours, observations, thoughts or feelings. When a recall method is used, rather than one where data are reported at the time of occurrence, data are likely to suffer from the same limitations as conventional self-report questionnaires. Nevertheless, limited data for children's TV viewing, when reported by a parent or assisted by their parents, suggest moderate to high reliability and validity when tested against direct observation and objective measures.[21] EMA methods, discussed in detail by Shiffman *et al.*,[36] have the following characteristics: (i) data are collected in ecologically valid ('real-world') settings; (ii) assessment is made of current or recent behaviours; (iii) time periods ('moments') are selected based on the research question of interest (e.g. specific behaviours or set time periods); (iv) multiple assessments are made over time.[37–40] In a study by Biddle and colleagues,[37] pilot data suggested that the 15-minute momentary time samples method provided accurate estimates of duration of the main behaviours compared with estimates derived from a minute-by-minute diary.

A clear advantage of EMA is in assessing specific behaviours as they occur, or very close to when they occur, as well as measuring the temporal, location and social context. Limitations of EMA include the potential for reactivity, mainly through the intense 'self-monitoring' that it entails, and compliance may be challenging given the high degree of participant burden. The significant researcher burden and economic costs associated with data entry and processing also limit the applicability of EMA-based methods in large-scale studies.

Objective methods

To address some of the limitations associated with self- or proxy-reported sedentary behaviour, objective methods of measurement are increasingly being used. This section summarizes the literature on the use of such devices in the epidemiological context.

Accelerometers

Accelerometers are small lightweight devices that are usually worn on an elastic belt positioned on the hip or lower back. Accelerometers measure the frequency and amplitude of acceleration of the body segment to which they are attached and often integrate this information in the form of movement 'counts'.[41] Accelerometers can be used to estimate the total volume of sedentary behaviour through the accumulation of low movement counts at specified cut points. They can also be used to detect short incidental breaks in sedentary time, defined by periods where movement counts exceed the specified threshold, which may not be feasibly recorded by self-report measures.[42] In addition, as the collected information is stamped with real time, specific segments of the day or week can be extracted, such as after school or time at work. There are many accelerometers on the market suitable for use in epidemiological research, although the ActiGraph (ActiGraph LLC, Pensacola, FL, USA) has been the most widely used to date. Key issues in the use of accelerometry for the assessment of sedentary behaviour relate to device initialization, post-processing, signal feature extraction and inference of specific outcome variables.[43] There is a lack of consensus as to the most appropriate accelerometer data-processing protocol, limiting comparability between studies and hindering evidence synthesis. Nonetheless, accelerometers are now being used to assess sedentary time in large-scale surveillance studies.[8,44]

Previously, it was necessary to specify the sampling frequency (epoch) during device initialization, but in newer accelerometer models (e.g. ActiGraph GT3X+) that record raw acceleration data, the epoch is overlaid during post-processing. A significant effect of epoch length on accelerometer-determined sedentary time has been reported, but findings are inconsistent, and the most appropriate sampling frequency for determining sedentary time has yet to be established.[45,46] In general, however, it is beneficial for researchers to collect data in as short an epoch as possible, as this provides information on exposure at the highest possible resolution. Moreover, data collected under shorter epochs can be summed into longer epochs, facilitating the process of directly comparing findings across studies. Importantly, data collected using longer epochs cannot be partitioned into shorter time frames. In the absence of a consensus regarding optimal epoch length, data collection using the shortest possible epoch, although potentially leading to the need for additional data processing, provides an opportunity for data to be re-integrated and compared between studies that would not otherwise be possible.

The monitoring period for accelerometer-based assessments of sedentary time has typically been 7 days,[8,47–51] with participants included in subsequent analyses if they provided sufficient data for at least 3–5 days (see discussion later). However, Matthews *et al*. recommend that at least 7 days of monitoring may be required to obtain reliable estimates of habitual time spent 'inactive' by adults, suggesting that current studies may have under-sampled the behaviour of interest.[52] In older adults, it has been suggested that 5 days are sufficient to accurately predict average daily sedentary time by accelerometry.[53] A recent study in children aged 6–8 years found that 3 days of monitoring provided 73% reliability for estimates of percent time spent sedentary using the ActiGraph GT1M.[54] Further work is required to examine between-day variability in sedentary behaviour patterns (e.g. weekday versus weekend) and possible seasonal variation, both of which will have implications for the monitoring period required.

In studies with children, the number of hours of monitoring required for inclusion of a day in analysis has been variable, ranging from 6 to 10 h/day.[49,51,55,56] However, a shorter day may be reasonable depending on the age of the child (young children having fewer waking hours than adolescents or adults). In adults, a minimum of 10 h of wear time has usually been required.[8,47,57] Identification of non-wear time is typically conducted by selecting a period of consecutive zero counts above which it is deemed that the device must have been removed. These segments of zero counts are then removed from further analysis. In studies concerned with estimating sedentary time, non-wear criteria have varied from 10 to 60 min of consecutive zero counts.[8,58] Using strings of zero counts to indicate non-wear time, however, is problematic because continuous zero readings may occur for a number of reasons.[59] Importantly, continuous zero counts may be recorded when a participant is sitting or lying (while wearing the device), potentially resulting in the erroneous removal of sedentary time data because of misclassification as non-wear time. Improved methods of identifying non-wear time are needed. One possible solution is to combine motion sensing with physiological assessments (such as HR[60]) wherein the absence of physiological data may be used to signify non-wear time.

A number of accelerometer cut points have been proposed for defining sedentary time in children and adolescents, varying from 10 to 1592 counts per minute (CPM).[61–69] Differences in the choice of calibration activities, criterion measures, statistical analyses and participant characteristics likely account for the diversity of cut points proposed to date. In general, it appears that studies using direct observation as the criterion measure have settled on higher cut points than studies using EE-based methods, but these have been limited to laboratory-based simulations of free-living behaviour.[68] Neither of these approaches are optimal criterion measures. Direct observation is not a wholly objective method, as it requires careful attention to intra- and inter-rater reliability. EE-based methods, while objective, are insufficiently sensitive to postural allocation and limited for distinguishing sitting from quiet standing.

Using the ActiGraph (uni-axial models), a count threshold of <100 CPM is commonly applied to denote sedentary time in adults.[8,47,48] This cut point has also been proposed for the classification of sedentary behaviour using the Actical activity monitor (Mini-Mitter, Bend, OR, USA).[70] However, despite the widespread use of this cut point, this value was not empirically derived, and studies reporting the validity of this cut point in adults are limited.[8,71] Recently, Kozey-Keadle *et al*.[71] assessed the criterion validity of a number of ActiGraph (GT3X) cut points (50, 100, 150, 200 and 250 CPM) for defining sedentary time against direct observation in a small sample of adults ($n = 20$). Findings indicated that the ActiGraph 100 CPM cut point underestimated sedentary time by 4.9%. The cut point with the lowest bias was 150 CPM, which overestimated sedentary time by 1.8%. A recent study by Oliver *et al*.[72] investigated sedentary behaviour cut points for the Actical accelerometer (hip mounted), using the activPAL (thigh mounted; PAL Technologies Ltd, Glasgow, UK) device as the criterion measure. It was concluded that a threshold of 0 counts/15 s epoch provided the most accurate estimates of sedentary time. However, recognizing the potential difficulties a zero-count cut point would raise in terms of distinguishing non-wear time, the authors recommend a threshold of 0–5 counts/15 s epoch during periods when the device can be deemed to have been worn.

A key limitation of traditional (count based) accelerometers as a measure of sedentary behaviour is that they assess intensity of movement and thus are less able to distinguish between postures, such as sitting and lying or standing still. Consequently, periods of standing still may be misclassified as sedentary time and vice versa.[30,73] Newer models of the ActiGraph accelerometer (GT3X and GT3X+) include an inclinometer function, which classifies participants' posture into four categories (device removed, standing, lying and sitting). Preliminary evidence, however, indicates that the validity of this function is limited and may be influenced by point of attachment.[74]

Posture monitors

The activPAL is a small lightweight electronic device worn under clothing. It is attached directly to the skin on the midline of the anterior aspect of the thigh. The activPAL determines posture on the basis of thigh acceleration, including the gravitational component and uses proprietary algorithms (Intelligent Activity Classification) to classify time as sitting/lying, standing or stepping. Information on cadence, number of steps taken, sit-to-stand and stand-to-sit transitions and estimates of EE are also provided.

The activPAL has been shown to be a reliable and valid measure of step counts in adults.[75–80] However, relatively few studies have explored the criterion validity of the activPAL for measuring sitting time.[32,71,73] In one validation study, a mean percentage difference of 0.19% (limits of agreement: −0.68% to 1.06%) between the activPAL monitor and direct observation for total time spent sitting was reported.[32] More recently, Kozey-Keadle and colleagues[71] examined the validity of the activPAL in assessing sedentary behaviour and detecting reductions in sitting time. The activPAL output was highly correlated with direct observation ($R^2 = 0.94$) and accurately identified investigator manipulated reductions in sitting time. Although limited in number, these studies provide promising preliminary evidence that the activPAL may be a valid tool for the assessment of sedentary behaviour in adults.

Research examining the reliability and criterion validity of the activPAL for measuring sitting time in young people is currently limited, though studies are beginning to emerge.[81,82] Davies *et al*.,[81] for example present validity data from 30 pre-school children who were videoed for 1 h undertaking usual activities in nursery school while wearing an activPAL. The activPAL demonstrated 87% sensitivity, 97% specificity and 96% positive predictive value for time spent sitting/lying, suggesting that this device may also be a valid measure of sitting time in children.

Although limited at present, the evidence suggests that the activPAL is a useful measure of sedentary behaviour (specifically sitting time) that could be utilized in a variety of contexts. Future research should aim to establish its validity, reliability and responsiveness for measuring sedentary behaviour in different populations and in different settings. Similar to other accelerometer-based methods, the activPAL does not provide information on the type of behaviour being undertaken or the social or environmental context in which it occurs.

HR monitoring and combined HR and movement sensing

The assessment of human HR as a method for studying behaviour has a long history.[83,84] Most epidemiological efforts, however, have concentrated on estimating total EE or time spent at moderate to vigorous intensity level (i.e. EE > three metabolic equivalents), typically using the flex-HR method.[85] The individually established flex-HR point (a discriminatory threshold between rest and exercise) determines when data from free-living behaviour are translated as EE at rest or according to an established regression line from an exercise test. In free-living conditions, it has been shown that most time is spent below the flex-HR point, even in children.[86] Time below flex-HR has been used to estimate sedentary behaviour and found to be associated with insulin resistance.[87] This measure of sedentary behaviour generally has high specificity but low sensitivity.

All strengths and limitations of HR monitoring and movement sensing apply equally to combined sensing data when these data streams are analysed separately. Here, we refer to the specific utility of combined sensing data for assessing sedentary behaviour when the HR and movement data are analysed together. This includes the initial inference on whether the monitor is worn, which can be made with greater certainty in the presence of both biomechanical and physiological sensor information.

Several studies have investigated the utility of combined HR and movement sensing to accurately assess physiological intensity across a wide range.[88–91] Defining sedentary behaviour in caloric terms (e.g. time spent at one metabolic equivalent or below) enables sedentary outcome variables to be derived from these methods. Time spent in the lowest branch of the branched model may be used as a pragmatic measure of sedentary behaviour, irrespective of its ability to estimate physical activity intensity.[92] To date, the utility of combined HR and movement sensing as a measure of sedentary behaviour has not been fully explored. Further work exploring the validity of this approach in diverse populations and settings is warranted.

Multi-unit monitors

The utility of multi-site/multi-sensor devices has been examined widely in the clinical setting (e.g. mobility assessments in older adults[93]), but their potential in the epidemiological domain is largely unknown. Typically, these devices use multiple accelerometers, inclinometers or physiological sensors attached to various points on the body. Sensor signals are then integrated to enable classification of different postures and types of movement. A number of such devices have been developed and examined for their accuracy in detecting posture and activity (both activity type and EE) in controlled settings.[33,94–98] However, the validity and feasibility of using these devices under free-living conditions has not been extensively tested. Limitations in battery and memory capacity and the computational and analytical complexity associated with processing multi-sensor data also limit their applicability in an epidemiological context at present. These devices may, however, be valuable as criterion measures in the validation of other sedentary behaviour measurement tools. For example, the Intelligent Device for Energy Expenditure and Activity (IDEEA; MiniSun, Fresno, CA, USA) has demonstrated 98% accuracy in classifying 32 different types of activity and postures under laboratory conditions.[33] Matthews *et al*.[8] reported a small unpublished study in which the convergent validity of the ActiGraph (model 7164) 100 CPM cut point for sedentary behaviour was compared against the IDEEA monitor in 19 free-living adults. The ActiGraph and IDEEA monitors displayed similar values for time spent sedentary (8.63 and 8.53 h/day, respectively), and there was a moderate association between the two devices ($r = 0.59$). Further development and validation work are required to examine the utility of multi-unit devices in field settings.

New and emergent methods

As we further examine the mechanisms linking sedentary behaviour to health, new measures and analytic methods may be needed to capture nuanced features of the behaviour and unpack the hypothesized causal pathways. For example, informed by evidence indicating that breaking up prolonged periods of sitting is associated with better cardiometabolic health,[42] new self-report measures are being tested that quantify breaks in sitting and not just the total exposure.[28] In terms of future developments, advances in sedentary behaviour assessment, particularly with regard to objective monitoring, will likely mirror those observed in computing and information technology more broadly. Accordingly, three emergent trends can be identified, namely the miniaturization of new devices, interoperability of existing devices and advanced computational methods. Here, we do not consider the development of specific new tools but rather explore how these broader trends may influence sedentary behaviour assessment in the future.

Miniaturization of new devices

Moore's law[99] continues to predict with some accuracy that electronic devices will become smaller, more sophisticated and cheaper every 12–24 months. Indeed, technology for data capture, processing and storage often outpaces our ability to describe it in the scientific literature. It is highly likely that disposable omnidirectional accelerometers with inclinometric or gyroscopic capabilities will soon cost less than printing, sending, collecting and entering data from a paper survey. There are already commercially available accelerometers with advanced data capture capabilities available for <$100. Further feasibility and validity studies of such devices may be necessary before they can be applied in research settings. Because sedentary behaviour assessment requires accurate detection of posture rather than movement intensity, energy-scavenging disposable inclinometers that attach to the skin, much like a plaster/band-aid®, are now conceptually feasible and would have major implications for population-based studies in this field.

Interoperability of existing devices

Interoperability refers to the ability of different software and hardware packages to work together effectively without special effort on the part of the user. Rapid growth of the service-oriented architecture (and cloud computing) in computer science has enabled commercially distinct tools to start communicating with one another, yielding a data stream that contains more information than the sum of its constituent parts. For example, combining geolocation data with acceleration signals in mobile phones can provide information about the context of sedentariness (e.g. occupational sitting vs sitting at home), in addition to reducing systematic error in the exposure itself. Another promising approach is the distribution of external sensors that communicate with a participant's mobile phone to provide real-time assessments of sedentary behaviour. This places the burden of data acquisition, storage and management (the 'cyberinfrastructure') on the phone itself, reducing the cost of measurement and participant burden. Testing of these devices and applications is already underway (e.g. at the Massachusetts Institute of Technology; http://web.mit.edu/wockets/).

New computational methods

New statistical and computational methods aimed at better characterizing sedentary and physically active behaviours are being developed and tested. Alternatives to threshold-based methods of classifying accelerometer 'counts' have started to emerge, such as machine learning models.[100] In these classification systems, a set of signal features from the accelerometer are extracted and then used as inputs for inference schemes, which are trained on annotated data. These techniques have been applied most frequently with multi-unit devices, but a small number of studies have used these methods to classify activity type from a single accelerometer.[100–105] For example, Pober *et al*.[104] were able to classify four types of activity (walking, walking uphill, vacuuming and computer work) with 80% accuracy using a hidden Markov model based on 1-s data collected with a single waist-worn ActiGraph (model 7164) accelerometer. These preliminary findings indicate the potential of pattern recognition methods to improve classification of sedentary time in epidemiological studies. Although these processes are analytically complex, the utility of pattern recognition in characterizing epidemiological data derives from the application of pre-determined algorithms developed from training data sets that are generalizable to large populations. However, more validation work is needed on large samples under free-living conditions that contain behaviours validated against direct observation. Novel methodological approaches, e.g. SenseCam (a data capture tool worn around the neck that automatically records time-stamped, first-person point-of-view images[106]), may be valuable in addressing some of the difficulties associated with more traditional approaches to direct observation.

Conclusion

Advancement in the epidemiological study of sedentary behaviour requires the development and application of accurate methods of measurement. In this article, we have described and evaluated the various methods of measuring sedentary behaviour applicable in the epidemiological context, highlighted areas in need of further study and discussed new and emerging themes in this field. Assessment of sedentary behaviour by self-reports is limited by, among other things, the ubiquitous nature of these behaviours, which may be unremarkable, intermittent and incidental and therefore difficult to recall. Traditional survey methods may be surpassed by new technologies that can provide, for all population groups, second-by-second information on posture, movement (or lack of movement) and patterns within and between days. Specific behavioural measures remain essential nonetheless for monitoring compliance with screen time recommendations and for providing additional information on the social and environmental context in which the behaviour occurs. New and emergent technologies show considerable promise in sedentary behaviour assessment, but challenges regarding attaining compliance with measurement protocols and the development and application of complex analytical methods remain.

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